THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Material metabolism of residential buildings in Sweden

Material intensity database, stocks and flows, and spatial analysis

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Cover: Street art that depicts a distorted view of the globe, zoomed in on the Nordic Atlantic islands and Scandinavian Peninsula. The image was crafted on a wall by uncovering the concrete texture from the white paint. Artist: unknown. Photo: Paul Gontia.

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Abstract

Construction materials are used for the expansion and maintenance of the built environment. In the last century, construction material stock has increased globally 23-fold. Given the current situation, the accumulated stock can be viewed as a repository of anthropogenic resources, which at the end of life could be re-circulated through the economic system to minimize the inflow of raw materials and the outflow of waste. A major step toward increased material circularity is the development of the supporting knowledge infrastructure. For this reason, research has focused on developing methods intended for exposing the material metabolism, namely, estimating the stocks and flows and analyzing the spatial and temporal dynamics of stocks and flows.

Residential buildings comprise a large share of the built environment. However, the material metabolism of these structures has remained unknown in many geographical contexts. Therefore, in this thesis, a bottom-up approach is employed to uncover the metabolism of residential buildings in Sweden. This goal is achieved through three methodological steps. First, a material intensity database is assembled based on architectural drawings of 46 residential buildings built within the period 1880–2010 in Sweden. Second, the stocks and flows are modeled with spatial and statistical inventory data and the developed material intensity database. Third, new spatial analysis approaches to the stocks and flows are conducted within urban and national boundaries. For the urban context, material stock indicators defined at the neighborhood level are clustered with well-known algorithms. At the national level, eight settlement types are considered to indicate the spatial dynamics.

The developed database indicates historical trends in terms of the material intensity and composition for residential buildings in Sweden. Moreover, the results contribute to establishing a global database and, through an extended international cross-comparison, to the understanding of how the material intensity and composition of residential buildings differ geographically. Furthermore, the stocks and flows are estimated in million metric tons at different administrative boundary levels. Among the six categories considered, mineral-binding materials, such as concrete, comprise the largest share of the accumulated stock. Finally, spatial differences in material stock composition are depicted in urban geography and nationally, among the eight settlement types. At national level, densely built-up corridors are identified, which should be used for enhancing material circularity.

This thesis contributes with data source exploration, methodological development, and critical analyses, relevant to researchers, policy makers, and practitioners interested in a more sustained metabolism of construction materials in the built environment.

Keywords: Material stock, material flow accounting, anthropogenic metabolism, bottom-up modeling, material intensity database, spatial analysis, clustering algorithms, construction materials, built environment, residential buildings, single-family buildings, multi-family buildings, urban stock, human settlements, and Sweden.

List of publications

This thesis is based on the following articles:

Article I
Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., Österbring, M. (2017) Material-intensity database of residential buildings: A case-study of Sweden in the international context, Resources, Conservation & Recycling 130: 228–239. Doi: https://doi.org/10.1016/j.resconrec.2017.11.022

The main aim of Article I is to construct a historical material intensity database for residential buildings in Sweden. Moreover, particular attention is paid to interpretation, sensitivity, and contextualization of the database. The results show specific historical trends for material intensity for both single family and multifamily residential buildings. Sensitivity analysis indicates that material intensity coefficients of single family residentials are highly influenced by parametric changes in building's structure. Discrepancies in results from studies worldwide suggest that further similar work is needed.

Article II
Gontia, P., Thuvander L., Ebrahimi B., Vinas V., Rosado L., Wallbaum H. (2019) Spatial analysis of urban material stock with clustering algorithms - A Northern European case study, Journal of Industrial Ecology 23: 1328–1343. Doi: https://doi.org/10.1111/jiec.12939

The main aim of Article II is to showcase an innovative approach for spatial analysis of urban material stock. For this aim, material stock indicators are defined at neighborhood level and clustered with k-mean algorithms. With the proposed spatial analysis urban areas that have similar material stock characteristics (age, material composition, density, etc.) are depicted.

Article III
Gontia, P., Thuvander L., Wallbaum H. (2019) Spatiotemporal characteristics of residential material stocks and flows in urban, commuter, and rural settlements, Journal of Cleaner Production. Doi: https://doi.org/10.1016/j.jclepro.2019.119435

The main aim of Article III is to assess the spatial and temporal characteristics of residential stocks and flows by considering different settlement types. Sweden is used as a case study. The results show that there are differences in stocks and flows and stock's characteristics among the settlement types. Moreover, spatial hotspots of stock accumulation are identified in the geography of the nation.

Contribution report

The following contributions were made to the articles:

Article I: I collected a large share of the data from the architectural drawings, modeled the material intensity coefficients, conceptually developed the method, contextualized the topic to the research field, interpreted the results, and wrote all the chapters. Nägeli C. and Österbring M. collected data from the architectural drawings and provided technical advices on buildings and construction materials. Österbring M. also guided me to the two books that contain the architectural material, on which much of this work is based. Rosado L. reviewed on multiple occasions the manuscript and was of a great help for documenting the method. Kalmykova Y. contributed with language check and the final editing.

Article II: I conceptualized the topic, developed the material intensity coefficients for non-residential buildings, collected a part of the spatial data for buildings, developed the analytical approach, and wrote all the chapters. Ebrahimi B. participated with the spatial data, intensity coefficients, and stock modeling for road transportation system. Vinas V. contributed with the spatial data, intensity coefficients, and stock modeling for the pipes network of drinking water and wastewater. Thuvander L. contributed with spatial data for buildings, and reviewed on multiple occasions the manuscript. Rosado L. and Wallbaum H. gave advice on the method and reviewed the final manuscript.

Article III: I conceptualized the structure of the article, developed and documented the method, interpreted the results, and wrote all the chapters. Thuvander L. and Wallbaum H. contributed with ideas for further improvement of the article's content and structure, and reviewed on multiple occasions the manuscript.

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Paul

Abbreviations

BMF	Brick structure multi-family residential building
CLC	Commuter municipality to large city
CMF	Concrete structure multi-family residential building
CMT	Commuter municipality to medium-sized town
CST	Commuter municipality to small town
GFA	Gross floor area
GIS	Geographical information system
LC	Large city
MF	Multi-family residential building
MIC	Material intensity coefficient
MT	Medium-sized town
RM	Rural municipality
RMI	Rural municipality with a visiting industry
SF	Single-family residential building
ST	Small town
WBMF	Wooden-brick structure multi-family residential building
WMF	Wooden structure multi-family residential building

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1. Introduction

1.1. Background and research gap

Construction materials are used for the expansion and maintenance of the built environment. In the last century, the material stock has increased 23-fold, and annual inflows have grown by a factor of 34 (Krausmann et al. 2009; Krausmann et al. 2017). Due to economic and population growth, the stock is rapidly increasing in many nations (Fishman et al. 2016). Stock expansion is directly linked to high resource consumption (e.g., materials, water, energy, land, etc.), waste discharge, and local and global environmental impacts (Wiedenhofer et al. 2015; Reyna and Chester 2015; Heeren and Fishman 2019; Mastrucci et al. 2017).

When considering the side effects of stock expansion, questions have been raised regarding the sustainability of the business-as-usual practices employed by the industries and governments involved. To address this issue, it is necessary to overcome the current linear practices of material utilization through an increase in circularity. The notion of material circularity has been conceptualized through analogies to other fields of science, such as biology and ecology. For instance, in reference to naturally evolved open systems (e.g., biological bodies, ecosystems, etc.) in which materials are indefinitely recirculated with little waste and no environmental impact (Lifset and Graedel 2002; Fischer-Kowalski 1998). This theoretical concept has been adopted by large governmental bodies, including the United Nations and the European Commission. For instance, within the 17 sustainable development goals (United Nations 2015b), several indicators (e.g., indicators 71 and 11.6 of goal 11 and indicators 12.2 and 12.4 of goal 12) have been suggested to coordinate international progress in the sustainable use of resources and waste management practices (United Nations 2015a). Similarly, the European Commission has recently adopted an action plan for the circular use of materials, which should be achieved through greater recycling and reuse (European Commission 2018). To attain material circularity is necessary to uncover the anthropogenic material metabolism – which refers to estimating material stocks and flows and analyzing the temporal and spatial dynamics of stocks and flows. In this respect, research has played a major role in developing the knowledge infrastructure – methods and databases – needed to determine the anthropogenic metabolism.

Construction materials accumulate in multiple components of the built environment such as buildings, roads, railroads, and drinking water and wastewater pipe networks. Past research has focused on single (Guo et al. 2014; Kleemann et al. 2016a; Nguyen et al. 2018; Ortlepp et al. 2016b) and multiple (Tanikawa and Hashimoto 2009; Tanikawa et al. 2015; Han and Xiang 2013; Huang et al. 2016; Wiedenhofer et al. 2015) components of the built environment. Residential buildings consume about half of the in-use building stock (Kleemann et al. 2016a; Huang et al. 2016; Tanikawa and Hashimoto 2009) and have therefore received considerable attention in the field (Arora et al. 2019; Condeixa et al. 2017; Bergsdal et al. 2007; Mastrucci et al. 2017; Ortlepp et al. 2016a; Mesta et al. 2018). However, the material metabolism of residential buildings remains unknown in many geographical contexts worldwide.

One of the several methods developed for calculating material stocks and flows is bottom-up modeling (Tanikawa et al. 2015). Bottom-up modeling is beneficial because of the diversity of temporal and spatial analyses that can be employed for the stocks and flows. However, this approach is also data demanding. Two major datasets are required in bottom-up modeling: (1) inventory data that describe the physical size of the stocks and flows in the assessed built environment and (2) the material intensity coefficients (MIC) database specific to each component of the built environment. While inventory data regarding the physical size – such as floor area, linear meters, or the heights of built environment components – can be found in statistics or extracted from geographical data supplied by cadastral offices, MIC databases, which reflect the historical changes in material intensity and composition in built environment components, are not provided by official organizations and have only been developed for a few countries. The unavailability of MIC databases is, therefore, a major impediment that should be overcome in order to extend the bottom-up modeling of the stocks and flows of construction materials in built environment.

Material stocks and flows in relation to construction materials in built environments are particularly reliant on spatial interpretation (Zhu 2014). Spatial analysis are needed because construction materials are used for building large structures, which have long lifespans and consequently stock over extended geographical areas. Different spatial approaches have been employed in multiple settlement contexts. Urban areas have received considerable attention in the field (Huang et al. 2016; Reyna and Chester 2015; Kleemann et al. 2016a; Mesta et al. 2018; Tanikawa and Hashimoto 2009) due to high urbanization trends (United Nations 2014) and high stock density in urban areas – which is relevant to the economy of scale and spatial proximity needed to bridge the supply and demand of secondary resources (Schiller et al. 2017). Han et al. (2018) have investigated the characteristics of the stocks and flows in urban, peri-urban, and suburban contexts in the case of a metropolitan area. Fishman et al. (2015) and (Han and Xiang 2013) have focused on sub-national administrative boundaries and have historically assessed the stock's regional disparity in relation to demographic and economic drivers. Others have deliberated the urban-rural dichotomy of material stocks and flows (Fishman et al. 2016; Huang et al. 2016; Schiller et al. 2017). Despite the current progress, many spatial aspects of the stocks and flows in both urban and national settings have not been addressed.

1.2. Aim, research questions, and methodological approach

The main goal of this thesis is to uncover the material metabolism of residential buildings in Sweden by employing a bottom-up approach. The second goal of this thesis is to contribute to the field with theoretical development – which is accomplished by data source exploration, methodological development, and enriching findings through analysis. Three research question categories have been formulated.

1. How does the material intensity and composition of residential buildings differ historically in Sweden? Which variables are most relevant for the MICs? How does the MIC database for Sweden relate to an international context? (Article I)
2. What are the quantities of construction material stocks and flows in residential buildings within different administrative boundaries? What are the characteristics (material composition and age distribution) of the in-use stock in the assessed case studies? (Articles II and III)
3. How do stocks and flows and their characteristics differ in different spatial contexts? What methodological approaches can be employed to refine the spatial characteristics of construction materials on urban and national scales? (Articles II and III)

The research questions are addressed though several distinctive methodological steps (Figure 1). The steps are here succinctly presented and detailed in Section 3. First, a historical MIC database for residential buildings for the Swedish context is constructed based on architectural drawings and the density of construction materials. Second, material stocks and flows are modeled with the formed MIC database and inventory data. Third, spatial analysis on urban and national stocks and flows are conducted. In addition, sensitivity and cross-comparison analyses are employed whenever relevant in each of these steps.

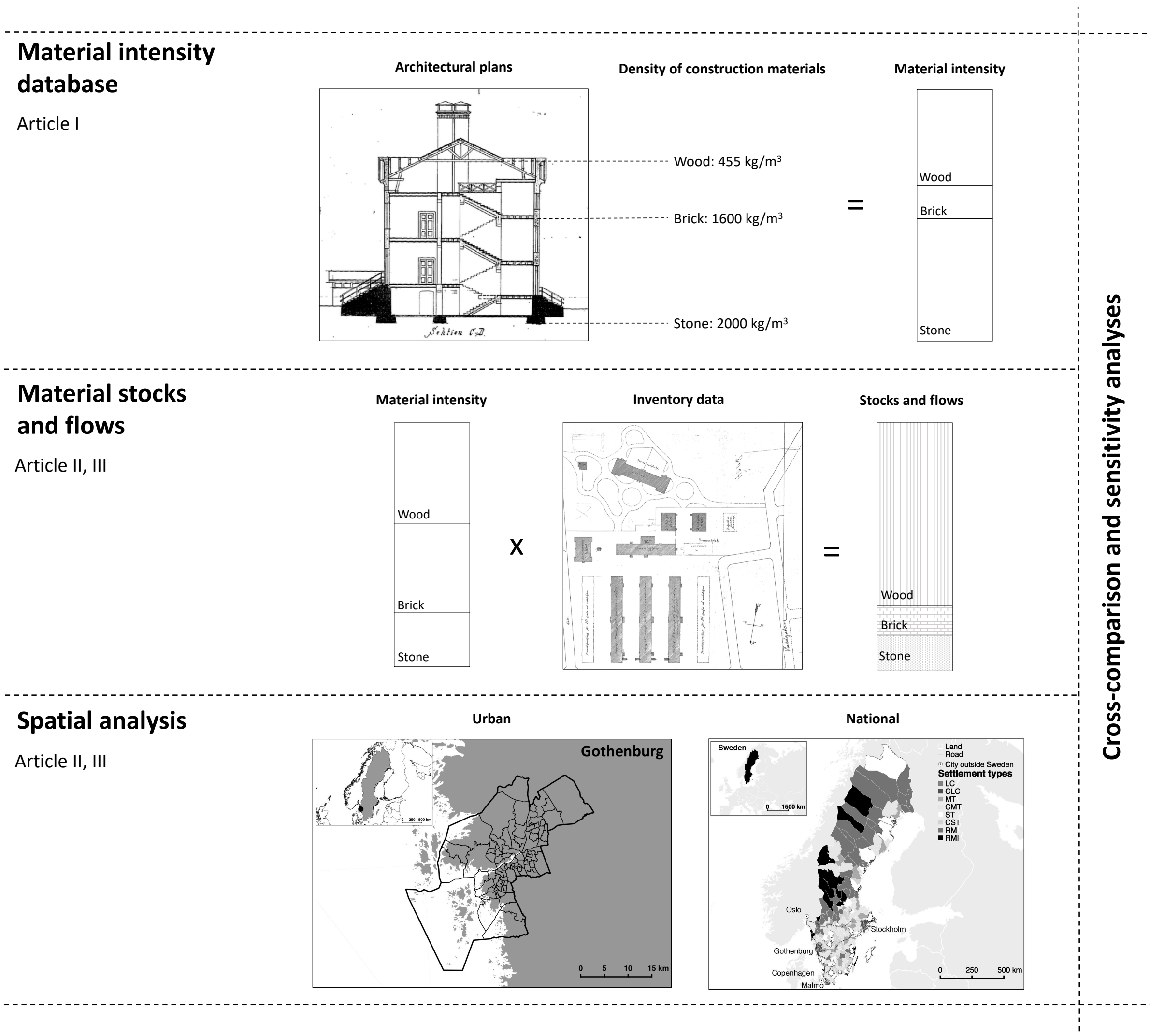


Figure 1. A simplified scheme on the methodological approach employed in this thesis.

1.3. Structure of this thesis

This thesis is structured as follows. In Chapter 2, an extended theoretical background on anthropogenic material metabolism is provided. Chapter 3 describes the methodological approach employed in this thesis. In Chapter 4, the main results and discussions are presented. Chapter 5 concludes the thesis, and Chapter 6 suggests further work.

2. Theory

The theory chapter begins with a description of historical changes in anthropogenic material metabolism. Next, the intellectual development of accounting methods used for determining the anthropogenic material metabolism is introduced. This chapter ends with a comparison of the methods developed for accounting and analyzing the stocks and flows of construction materials in built environments.

2.1. A short history of anthropogenic material metabolism: from circular to linear and back to circular

Anthropogenic material metabolism has changed considerably over time. To describe these changes, the material metabolism of prehistoric society, which is here referred to as the hunter-gatherer society, is compared to modern society, which is here referred to as the present state of the industrialized modern state. Figure 2 illustrates these changes and is used as the basis of this discussion.

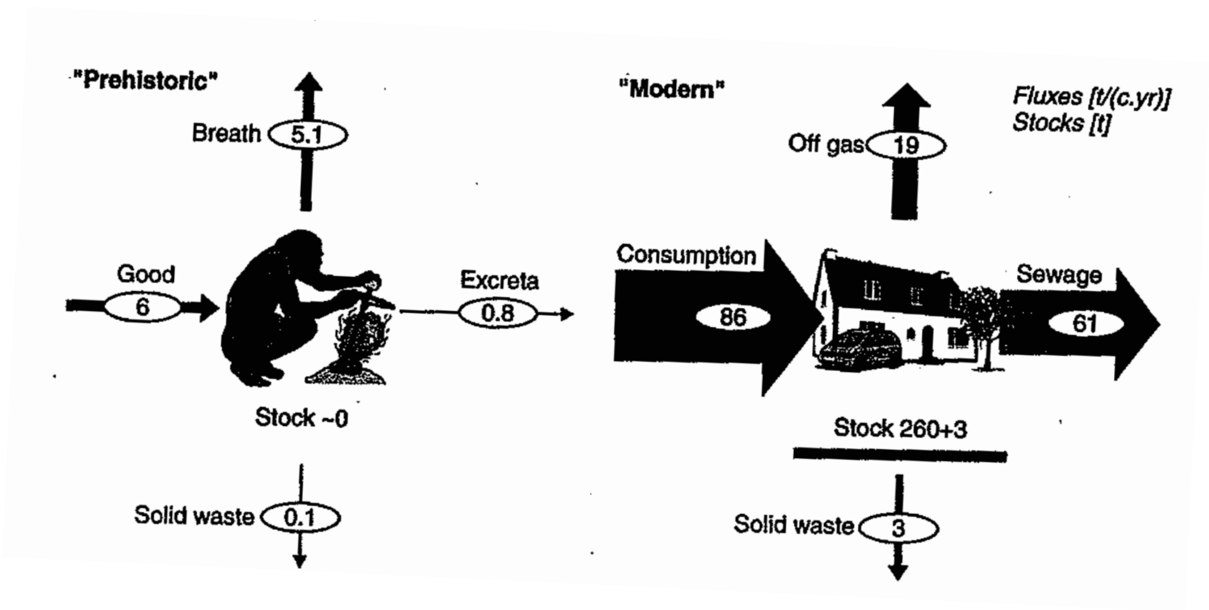


Figure 2: Side-by-side comparison of the prehistoric and modern anthropogenic material metabolism. Source: Brunner and Rechberger (2004).

The following differences in the material metabolism between the two societal organizations can be noted. First, the stocks and flows needed to support an individual have drastically increased since prehistory. The flows have increased by an order of magnitude. Whereas the stock was nonexistent in prehistoric times, it presently amounts to hundreds of metric tons per capita. Second, in prehistoric times, almost all the effort was allotted to feeding activities: humans were mainly occupied with maintaining the metabolism of their own bodies. In modern society, the turnover of materials extends beyond sustaining feeding needs; it has been externalized to supporting complex cultural activities. Third, in prehistoric times, the materials metabolized by humans were entirely organic and were recirculated in a closed loop through the functioning of ecosystems. Today, many of the materials utilized are highly concentrated mineral ores or fossil based (Krausmann et al. 2009), which are returned directly into the environment at the end of life. These materials are not organic and therefore do not decompose but persist in the environment. Fourth, artifacts were simplistic and handmade in prehistoric times. With the unfolding of modernity, which led to increased knowledge and technological development, material functions have become more fully understood and increasingly larger, and more complex artifacts have been built. Today, humans can sustain megacities, and build artificial satellites. Figure 3 presents a composed satellite image that depicts the Earth at night and the expansion of the built environment in the geography of the planet.

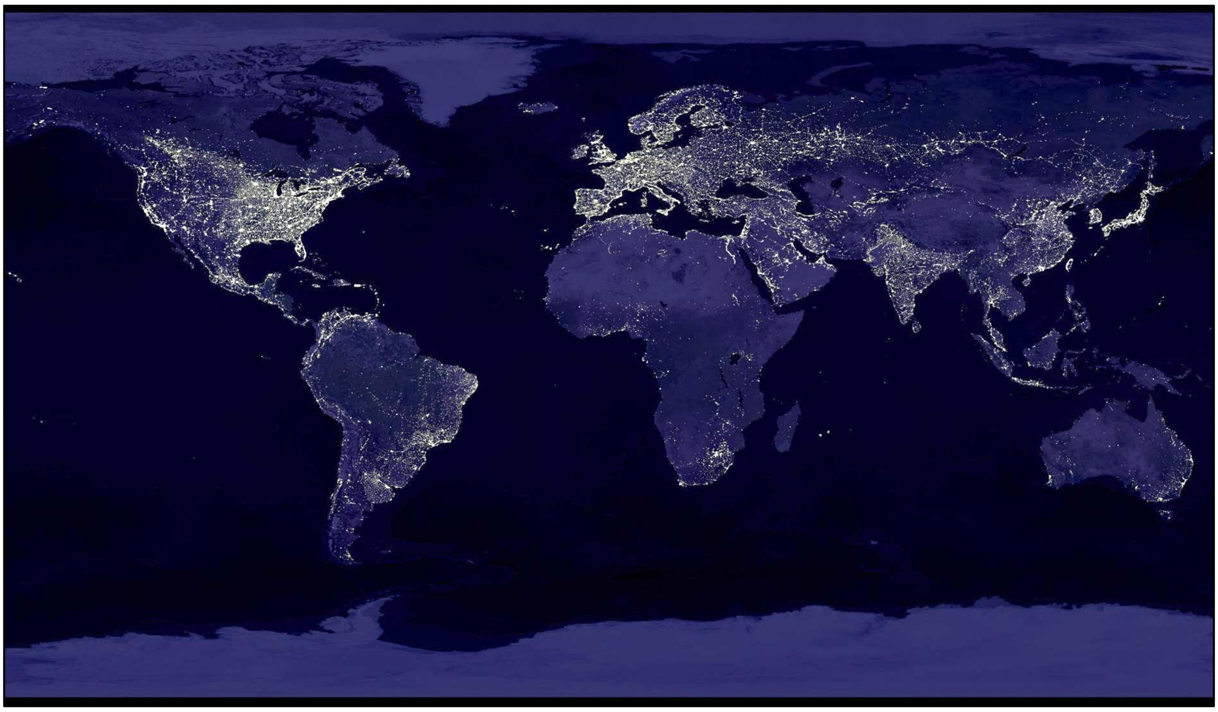


Figure 3: Earth at night, which depicts human activity through the built environment. Source: NASA/NOAA (2009).

Furthermore, Haberl et al. (2011) demonstrated that the initial phase of metabolic change was slow, expanding through many millennia from hunter-gatherer to agrarian societies. Considerable changes in material metabolism started with the industrialization of the modern society in the 17^{th} century after discovering the fossil energy carriers. A further acceleration in metabolic change occurred in the second part of the 20^{th} century after World War II (Haberl et al. 2011). It is important to highlight that as early as the beginning of the 20^{th} century, much of the metabolism was still mainly organic and renewable and only after World War II, the metabolism shifted to mainly mineral and fossil based (Haberl et al. 2011; Krausmann et al. 2009).

Thus, material metabolism from the prehistoric period to modern industrial society changed from small scale to large scale, from internal to external, from fulfilling mainly feeding needs to fulfilling complex cultural activities, from organic and decomposable materials to man-made and persistent materials, and from relatively simple and handmade artifacts to highly complex technologically derived artifacts. Moreover, whereas early social organizations experienced a slow change in metabolism, the modern industrial society exhibited rapid structural changes in metabolism. However, perhaps unintentionally, these changes in metabolism have been ignored. Humans have only recently understood that they are directly responsible for closing the material cycle to sustain the current societal organization. Whether the current social organization should be preserved is a question that is not addressed here.

2.2. Material metabolism: methodological development

A considerable portion of the research has focused on quantification methods of the anthropogenic material metabolism. These methods have at the bases the system thinking theory (Weinberg 1975) and can be defined as "systematic assessments of the flows and stocks of materials within a system defined in space and time" (Brunner and Rechberger 2004). However, the intellectual development of these methods took nearly two centuries. Fischer-Kowalski (1998) have demonstrated that material metabolism was first conceptualized in the fields of biology and ecology in the middle of the 19th century. Until middle of the 20th century, the concept was re-interpreted within the social sciences. For instance, by Karl Marx, who deliberated the transformation of nature through human labor and the exchange of commodities through the economic system (Marx 1964; Wachsmuth 2012). Material metabolism methods were applied to uncover the anthropogenic metabolism for the first time in the 1960s (e.g. Wolman (1965)) following the increasing environmental awareness of that period (Carson 1962; Meadows et al. 1972). It took another quarter of a century for this pioneering work to be legitimized and mainstreamed within academia and practice (Fischer-Kowalski and Hüttler 1998). Today, material stocks and flows accounting are commonly applied to analyze the anthropogenic metabolism in many spatial and temporal contexts and for diverse material types, artifacts, and structures.

2.3. Approaches employed for analyzing the metabolism of construction materials in the built environment

Large man-made structures such as buildings and infrastructures, also known as the built environment, have received considerable attention in the field. Several methods have been developed and have been classified in the literature on several occasions. Tanikawa et al. (2015) have distinguished four methods based on the approach and the interrelated data used: top-down accounting, bottom-up accounting, demand-driven modeling, and remote sensing approaches. Augiseau and Barles (2017) have considered the temporal dimension of the assessments (static/in-use, retrospective, and prospective) and have distinguished between stock-driven and flow-driven modeling. The classification by Tanikawa et al. (2015) is a more complete description of the methods employed in the field; therefore, these methods are introduced below. Whenever relevant, lines are drawn to Augiseau and Barles (2017) classification and the contexts in which each method has been employed.

1) Top-down accounting is based on economy-wide material flow accounting (European Commission 2001), which was developed by Eurostat. Within this method, the annual addition to stock is determined from the material balance of inflows and outflows that transpose the defined spatial boundary of interest (e.g., nation state, region, etc.). To estimate the in-use material stock at a point in time, the series of annual addition to stock are summed up. This method is flow driven and commonly used for both retrospective and prospective estimates. It was successfully employed for larger geo-spatial contexts such as multiple countries and extended time series (Fishman et al. 2016; Krausmann et al. 2017).

2) Bottom-up material stock accounting is based on two main datasets: the inventory of the built-environment components (buildings and infrastructures) in a defined space and time and the MICs specific to each component. This method is a stock-driven method, is used for in-use and retrospective assessments, and was successfully employed for detailed spatial analysis of material stock, such as age, material composition, stock density and stock expansion. (Kleemann et al. 2016a; Tanikawa et al. 2015; Tanikawa and Hashimoto 2009; Reyna and Chester 2015).

3) Demand-driven stock modeling is based on MICs, similar to the bottom-up method. However, the inventory of in-use stock, for the geographical location under investigation, is derived from socio-economic variables (e.g., demographics, affluence, etc.). Demand-driven modeling is predominantly used for estimating the temporal dynamics of material stock and for determining the input and output flows of construction materials (Bergsdal et al. 2007; Hu et al. 2010; Müller 2006).

4) Remote sensing approaches estimate the stock based on the artificial light reflected by the built environment. In the first step, statistical correlations between an area with already estimated material stock and the reflected nighttime light are identified. In the second step, these correlations are used to estimate the stock in other geospatial areas where material stock information is not available. This method has been used solely for in-use stock estimates. Moreover, it was employed for spatial analysis in cases of data scarcity and for large-scale stock estimates, beyond considering geopolitical boundaries (Takahashi et al. 2010; Yu et al. 2018).

For this thesis, a bottom-up method was chosen to reveal the metabolism of residential buildings in Sweden. Consequently, it is important to discuss some of the advantages and disadvantages of bottom-up modeling in comparison to the other approaches mentioned above.

- The bottom-up approach allows for a detailed analysis of both the temporal and spatial dimensions of stocks and flows. The remote sensing approach can best indicate the spatial dimension, whereas top-down and demand-driven approaches can best indicate the temporal dimension. The limitation of the bottom-up approach is the large amount of data needed. This method is therefore less suitable for assessments of multiple nations for which top-down, demand-driven, and remote sensing could be more appropriate.

- The bottom-up approach allows for a more detailed analysis of the built environment. This method can indicate in which built environment component construction materials accumulate. For example, how much of the total stock has accumulated in different structures (buildings or other infrastructures), types of buildings (residential or nonresidential), and residential types (single-family or multi-family buildings) can be indicated. Furthermore, the bottom-up approach provides more elaborate information regarding the structural location of construction materials within buildings (e.g., roof, façade, basement, etc.). Finally, the method can be employed for the detailed spatial analysis of the stocks and flows down to the building level. None of the other methodological approaches can provide a similar detailed analysis of the stocks and flows.

- Although the large inventory data and MIC databases can be viewed as an impediment to further application, a bottom-up approach is methodologically less sophisticated and requires more basic datasets for modeling than any of the other methods. Night light data needed for the remote sensing approach are not easily available and rely on advanced statistical knowledge. The top-down approach is based on rich statistical data, which are not available in many countries and are unavailable for sub-national assessments. On the contrary, MIC databases can be developed with local expertise and materials. Similarly, geographical information system (GIS) data can be found in many data centers around the world.

3. Methodology

In the following subsections the methodology employed in this thesis (Figure 1) is further explained through text, figures, and equations.

3.1. Formation of a material intensity database

The MIC database for residential buildings was derived from architectural plans and the densities of construction materials. The process consisted of 6 steps, which are summarized below.

a) *Database structure.* The data used to populate the MIC database were extracted from two books (Björk et al. 2009; Björk et al. 2013), which have documented the architectural trends and construction technology of single-family (SF) and multi-family (MF) residential buildings erected in Sweden during the time period 1880–2010. In these architectural books, 12 typical SF and 34 typical MF buildings were selected as the most representative in Sweden, based on an analysis of thousands of real estate advertisements and plans collected from over 30 municipalities (Björk et al. 2009; Björk et al. 2013). For the results representation, the 46 typical buildings were categorized according to three features: residential building type (SF or MF), type of structure (wooden: W, wooden-brick: WB, brick: B, and concrete: C), and construction period (decade intervals). These features were also used to code the buildings. For instance, a MF building of brick masonry commonly built in the 1910s was coded as BMF1910. If multiple buildings dated back to the same decade, an additional numerical indicator was added to the code (e.g., BMF1930.1 and BMF1930.2).

b) *Inventory*. In this step, data on the construction materials of each typical building were collected. The type and dimension of the construction materials were tabulated. The inventory tables were then used to produce spreadsheets, which were where the modeling of the database took place.

c) *Volume calculation.* From architectural plans and descriptive text, the dimensions of the construction materials for each building element were collected (see Table 1, (Gontia et al. 2018)). The dimensions were used to calculate the volume of each construction material with Equation 1:

$$V_{i,j,l} = B_{i,j,l} \times A_{i,j,l} \quad (1)$$

where $V_{i,j,l}$ is the volume of construction material *i*, part of building element *j*, for typical building *l*; $B_{i,j,l}$ is the thickness dimension of construction material *i*, part of building element *j*, for typical building *l*; and $A_{i,j,l}$ is the area of construction material *i*, part of building element *j*, for typical building *l*.

d) *Mass calculation.* The mass was derived from the volume of the construction materials and the corresponding density. The list of construction material densities was collected from diverse sources and can be viewed in Table 2, Article I. Equation 2 is a simplified mathematical representation of this step:

$$M_{i,k,j,l} = V_{i,j,l} \times D_{i,k} \quad (2)$$

where $M_{i,k,j,l}$ is the total mass of construction material *i*, part of material category *k* and building element *j*, for typical building *l*; $V_{i,j,l}$ is the volume of construction material *i*, part of building element *j*, for typical building *l*; and $D_{i,k}$ is the density of construction material *i*, part of material category *k*.

e) *MIC calculation.* The MICs were calculated using Equation 3 for each construction material and typical building. In this step, the total mass of a construction material in a building was divided by the gross floor area (GFA) of the building:

$$MIC_{i,k,j,l} = M_{i,k,j,l}/GFA_l \quad (3)$$

where $MIC_{i,k,j,l}$ is the MIC of construction material *i*, part of material category *k* and building element *j*, for typical building *l*; $M_{i,k,j,l}$ is the mass of construction material *i*, part of material category *k* and building element *j*, for typical building *l*; and GFA_l is the GFA of typical building *l*.

f) *Aggregation of MICs.* The MICs for each construction material were aggregated into material categories with Equation 4'. Six material categories have been used: wood-based materials, brick and ceramics, mineral-binding materials, stone and aggregates, iron and steel, and miscellaneous/others (e.g., glass, polymers, etc.). Details regarding the categorization of construction materials can be seen in Table 2, Article I. The MIC database was also aggregated with Equation 4'' to show the mass distribution among the building elements: foundation/basement slab, basement wall, basement ceiling, intermediate floor, top floor, internal wall, window, external wall, and roof. The MIC results are displayed aggregated in both ways.

$$MIC_{k,l} = \sum MIC_{i,k,j,l} \quad (4')$$

where $MIC_{k,l}$ is the sum of the MICs aggregated by material category *k*, for typical building *l*; $MIC_{i,k,j,l}$ is the MIC of construction material *i*, part of material category *k* and building element *j*, for typical building *l*.

$$MIC_{j,l} = \sum MIC_{i,k,j,l} \quad (4'')$$

where $MIC_{j,l}$ is the sum of the MICs aggregated by building element *j*, for typical building *l*; $MIC_{i,k,j,l}$ is the MIC of construction material *i*, part of material category *k* and building element *j*, for typical building *l*.

3.2. Calculation of material stocks and flows

Material stocks and flows have been modeled for diverse geographical and temporal boundaries. Depending on the boundaries assessed, a different MIC database structure and inventory data (GIS and statistical) have been employed in the modeling. Details on the preparations of the MIC database structure and inventory data done prior to modeling can be found in Articles II and III. A short generic description of the calculus completed for estimating the in-use material stock, retrospective stock, and material flows is provided below.

In-use material stock. The in-use stock was determined using the MIC database and inventory data. To increase the accounting accuracy and to expand the stock analysis, the following descriptive variables of the stock were used in the modeling: residential building types (SF and MF), age classes (e.g., before 1920, 1921–1950, 1951–1980, and after 1981), and material categories (e.g., wood-based, brick and ceramics, etc.). Equation 5 is a simplified mathematical representation of the calculus:

$$MS_{k,n,m} = \sum X_{k,n,m} \times C_{n,m} \qquad (5)$$

where $MS_{k,n,m}$ is the material stock for material category *k*, for residential building *n* and age class *m*; $X_{k,n,m}$ is the intensity of material category *k*, for residential building *n* and age class *m*; and $C_{n,m}$ is the inventory of residential building *n,* for age class *m*.

Retrospective stock. The retrospective material stock of the period was calculated using Equation 6 by differentiating the in-use stock estimated for the extreme years of the period. In this case, the retrospective stock was calculated for the period 1991–2017 (Article III). The interval was determined according to the availability of inventory data.

$$MS_k^{t-t_0} = MS_k^t - MS_k^{t_0} \qquad (6)$$

where $MS_k^{t-t_0}$ is the material stock accumulated in the interval t-t_0 for material category type *k*; MS_k^t is the in-use material stock for the year *t* for material category type *k*; and $MS_k^{t_0}$ is the in-use material stock for the year t_0 for material category type *k*.

Material flows. Material inflows and outflows have been determined in the literature through different approaches, depending on data availability. In the present case, the inflows were determined directly through statistical inventory data that represent the newly constructed residential buildings. To estimate the inflows, the inventory data were multiplied by the average MICs specific to the considered period (Equation 7). The outflows were mathematically derived by extracting the retrospective material stock from material inflow determined for the same period (Equation 8). As with the retrospective stock, the inflows and outflows were determined for the period 1991–2017. Note that the inflow refer only to materials that remained in newly constructed buildings and the outflows refer only to the materials due to demolition of buildings. Waste derived from construction activities is not included in the estimated outflows.

Similarly, construction materials due to maintenance activities of buildings are not included in the flow estimation.

$$MI_k^{t-t_0} = \sum X_{k,n} \times E_n^{t-t_0} \quad (7)$$

where $MI_k^{t-t_0}$ is the input material in the interval t-t_0 for material category k; $X_{k,n}$ is the intensity of material category k for residential type n; and $E_n^{t-t_0}$ is the inventory of newly constructed buildings in the interval t-t_0 for residential type n.

$$MO_k^{t-t_0} = MI_k^{t-\ t_0} - MS_k^{t-\ t_0} \quad (8)$$

where $MO_k^{t-t_0}$ is the output material in the interval t-t_0 for material category k; $MI_k^{t-\ t_0}$ is the input material in the interval t-t_0 for material category k; $MS_k^{t-t_0}$ is the material stock accumulated in the interval t-t_0 for material category k.

3.3. Spatial analysis and case studies

The spatial analyses were conducted for two different system boundaries and distinct methodological approaches. First, the spatial analysis was developed for an urban area by employing clustering algorithms (Article II). Second, the analysis was conducted for a national context considering different settlement types (Article III). An extended description of the two methods and a short description of the case studies in which the two approaches have been tested are provided below.

Spatial analysis of urban material stock with clustering algorithms. The aim of this analysis was to identify urban areas that have similar material stock characteristics. To capture the spatial trends, the urban stock was sectioned according to the neighborhood administrative boundaries. On the neighborhood level, a set of material stock indicators was defined:

- Material stock separated by material category: wood-based materials, brick and ceramics, mineral-binding materials, stone and aggregates, iron and steel, and miscellaneous/others;
- Residential building type: SF and MF;
- Age class: before 1950, 1951–1980, and after 1981.

Next, the indicators were clustered with k-mean algorithms (Hartigan and Wong 1979). Clustering is an unsupervised learning technique employed to partition a set of unclassified observations into homogenous subgroups. Finally, the formed clusters were attached to the neighborhoods to compose new maps intended for spatial interpretation.

The spatial analysis was performed for the in-use stock determined as of 2016. The 96 neighborhoods of the Gothenburg municipality were used as a case study (Statistics Gothenburg 2018). The city of Gothenburg is located on the west coast of Sweden (Figure 4). It is the second largest city in the country with an area of 447 km^2 and approximately 560,000 residents as of 2016 (Statistics Gothenburg 2016). The city has a diverse economy and accommodates the largest port in Northern Europe. Gothenburg is also culturally diverse with a high yearly inflow and outflow of inhabitants (Statistics Gothenburg 2016).

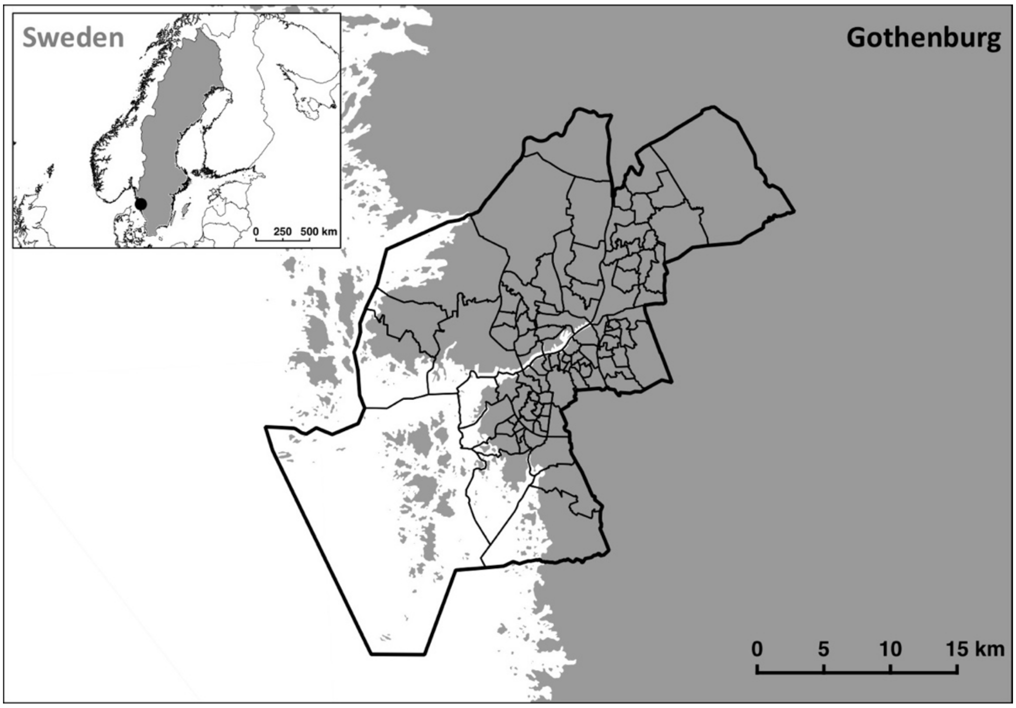


Figure 4: The geographical location of Gothenburg city in Sweden and the administrative boundaries of the 96 neighborhoods, which have been used to section the in-use urban stock of residential buildings.

Spatial analysis of national stocks and flows within different settlement types. A spatial analysis was conducted on a national level considering the 290 municipalities classified into eight settlement types (Figure 5) according to Swedish municipalities and county councils (SKL 2016). The classification of municipalities into settlements was done based on three mutually exclusive criteria: the number of inhabitants, spatial proximity, and commuting habits. In addition to these common principles, rural municipalities have been further separated based on the economic activity criterion. The settlement types are the following: large city (LC), medium-sized town (MT), small town (ST), commuting municipalities (CLC, CMT, CST), rural municipality (RM), and rural municipality with visiting industry (RMI). The in-use stocks were estimated for the year 2017. The retrospective stocks and the flows were estimated for the period 1991–2017. Sweden has the largest land area in Scandinavia and the third largest in Europe. The population is about 10 million. Economically, the country is diverse, with activities ranging from agriculture and industry to services.

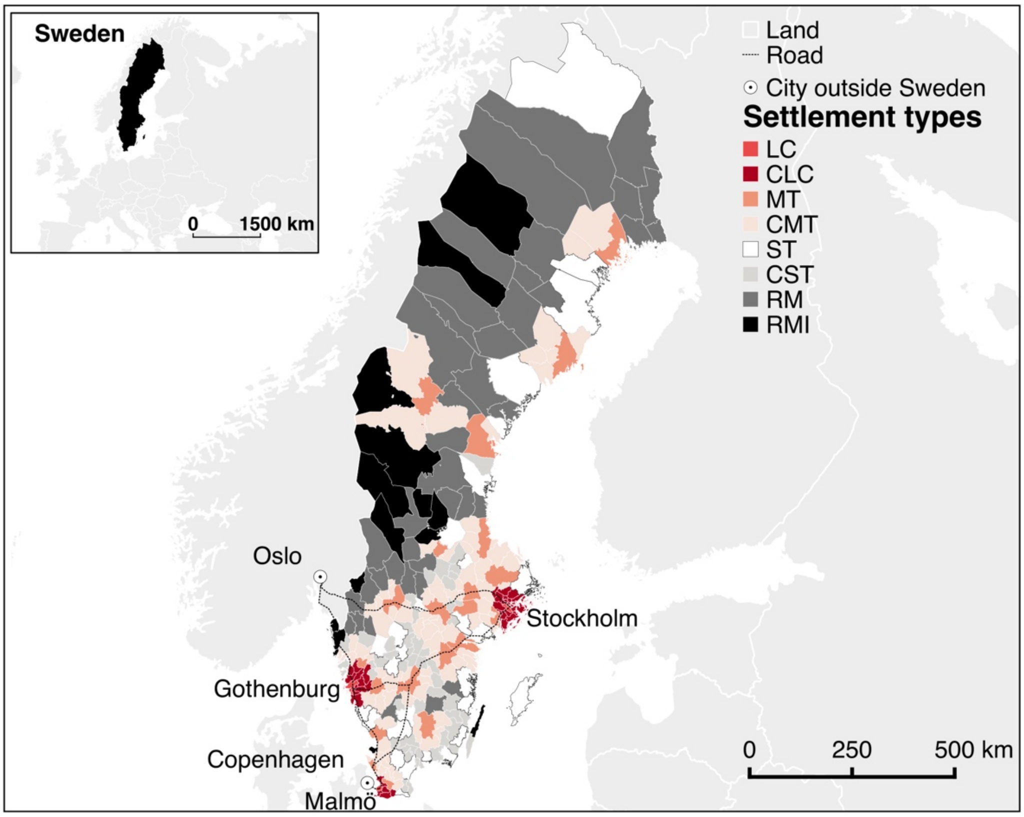


Figure 5: The municipalities of Sweden classified by settlement types. In the left-upper corner, Sweden is illustrated as located in Europe. The three largest metropolitan areas of Sweden (Stockholm, Gothenburg, and Malmö), two capital cities of the neighboring countries (Oslo, Norway and Copenhagen, Denmark), and the main road network connecting them are displayed on the map for discussion purposes.

3.4. Sensitivity and cross-comparison analyses

In all three methodological steps, cross-comparison and sensitivity analysis were performed. Sensitivity analysis was conducted to uncover variables that could influence the results. First, the analysis was employed in relation to the MIC database through alternating the structural variables (e.g. building's footprint size, number of floors, etc.) within a typical building (Article I). Second, in the case of the spatial analysis of urban material stock, several algorithms were tested to find out if and how different clustering algorithms affect the formed clusters (Article II). Last, a sensitivity analysis was employed for the age-based aggregated MICs to demonstrate how much database structure influences the modeled material stock (Article III). Cross-comparison analyses were performed to expand the understanding of the results within the international research and to validate the modeled results. These analyses were employed for the MIC databases (Article I), urban material stock (Article II), and material flows (Article III).

4. Results and discussion

4.1. Material intensity database

4.1.1. Main results

In Figures 6a and 6c, the MICs for the 12 SF and 34 MF residential buildings are displayed in mass (kg) per GFA (m^2), aggregated by material category. In Figures 6b and 6d, the MICs are listed as percentages (%), aggregated by building element. Because all the SF buildings included in the database have wooden structures, the MICs are presented in chronological order, from the end of the 19th century until the beginning of the 21st century. In the case of MF buildings, the MICs are distributed by the main structure types: wooden multi-family (WMF), wooden-brick multi-family (WBMF), brick multi-family (BMF), and concrete multi-family (CMF), and for each structure type, the results are displayed in chronological order.

The overall results indicate that the MICs differ for the two residential types. For SF buildings, an intensity decline over time can be seen (Figure 6). The decline can be attributed to changes in the structure of the buildings and the construction materials used. In relation to the material composition of SF buildings, mineral-binding materials are the most predominant for most of the past century. The exception is the period prior to the 1910s, for which stone and aggregates, used for the construction of basements, occupy the largest share (Figure 6). Wood-based materials demonstrate a decline in intensity, mainly due to the mid-century structural shift from load bearing to frame. The other material categories present alternating results due to large variations in the construction material used for different building elements (e.g., façade of brick or wood, roof covering materials of metal sheet and clay tiles, etc.). For MF buildings, the material intensity and composition vary according to the structure type (Figure 6). The highest average MICs can be seen for BMF, which displays the highest intensity of ceramics and brick, followed by CMF, which exhibits the highest intensity of mineral-binding materials. The lowest average values are exhibited by WMF and WBMF residential buildings. WMF, WBMF, and BMF building structures were all predominantly built in the period 1880–1940. After the 1940s, CMF buildings were most commonly built.

The mass distribution among different building elements also differs with the residential type, structure of the building, and period of construction (Figure 6). For SF buildings, basements and foundation elements comprise the largest proportion of the total MIC. This also suggests that a large proportion of the construction materials in SF buildings are in the ground. Over time, it is evident that the roof comprises an increasingly larger share of the MICs, which is explained by the lower intensity of the other building elements. The most influential structural change is that SF structures have been built without basements after the 1960s. For MF buildings, the mass distribution by building elements follows trends specific to the individual structure type of the buildings. Thus, for WMF and WBMF, the basement elements constitute the largest share of the total MICs. For BMF, a major part of the construction materials is found in the external walls, whereas for CMF, the largest mass is found in the intermediary floors (Figure 6)

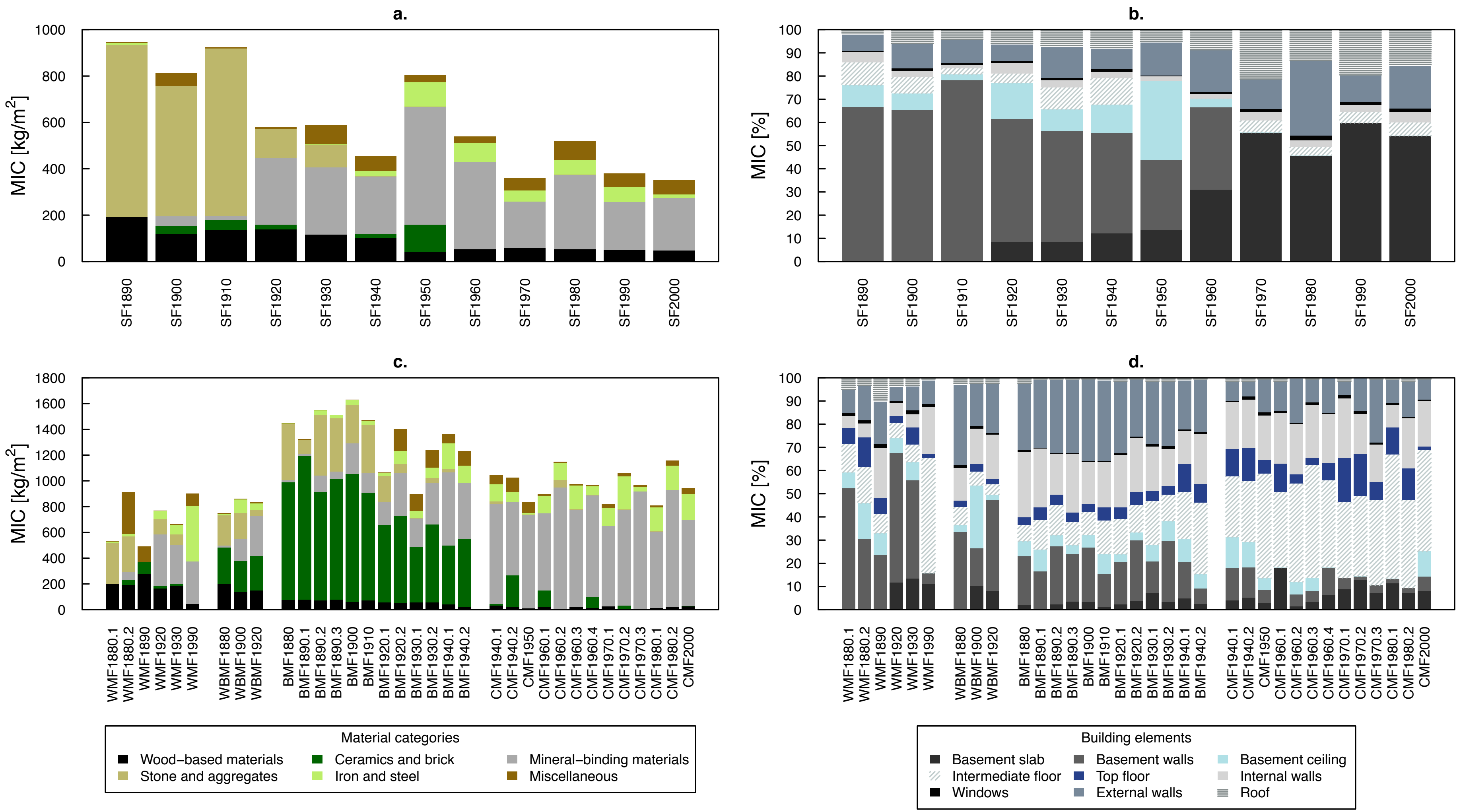


Figure 6. The MICs for the 46 typical buildings: (a) SF buildings aggregated by material category; (b) SF buildings aggregated by building element displayed as percentages (%) ; (c) MF buildings aggregated by material category; and (d) MF buildings aggregated by building element displayed as percentages (%); SF: single-family; WMF: wooden multi-family; WBMF: wooden-brick multi-family; BMF: brick multi-family; and CMF: concrete multi-family

4.1.2. Interpretation of the MIC database and lessons learned from practice

Although the construction of the MIC database for residential buildings in Sweden was accomplished to a large extent, the structure of the database should be further interpreted. The interpretation is important considering that the database is intended for further modeling of material stocks and flows. Therefore, the discussion expands not only on the initial interpretation of the database but also to the lessons learned from modeling in practice.

The database for SF is composed of a single typical building example for each decade. Therefore, the preferred way to interpret the SF buildings, historically, is to group them into cohorts. Major structural changes in buildings could be utilized as guidance. For instance, SFs built between 1880 and 1910 can be grouped together, as they all have stone basements and similar material compositions and mass distributions (Figures 6a and 6b). Furthermore, the shift from a load-bearing wooden structure (SF1890–SF1940) to a wooden frame structure (SF1950–SF2000) impacts the results and could, therefore, be used for grouping the SF buildings. These grouping trends were further discussed in sensitivity analysis (see Section 4.2, Article I), but for the sake of simplification, it can be concluded that grouping typical buildings into four decade intervals (SF1890–1910, SF1920–1940, SF1950–1970, and SF1980–2000) provides the optimal interpretation of the MIC results for SF buildings. Grouping into cohorts is also important when dealing with exceptional MIC results in a typical building. The most relevant example to this discussion is the SF1950 typical building, which presents the highest MIC results for mineral-binding materials (509 kg/m^2) due to its basement ceiling made of concrete (Figure 6a). In comparison, all the other typical SF buildings have a wooden basement ceiling and therefore a lower proportion of mineral-binding materials (the average for SF1920–SF2000 is 297 kg/m^2). For MF buildings, the number of typical buildings that overlap for a certain period is considerably higher than for SF buildings. Nevertheless, MF buildings have already been grouped based on their different structure types, and the historical trends have been outlined. Therefore, a further re-grouping seems unnecessary.

When the MIC database was used in the modeling of material stock, it was evident that multiple adjustments, beyond the initially observed trends, were needed. These adjustments depended on the inventory data, which describe the residential stock. For instance, in Article III, the inventory data for SF buildings were found only for the period before 1930. The period before 1930 does not match the 1880–1910 period – a period defined based on observed historical trends in the structure of SF buildings. For MF buildings, the information regarding the structure type of the buildings was not found in neither the statistical nor spatial data banks. Therefore, the database for MF buildings needed to be grouped into periods with overlaying building structures. For instance, in Article III, three different MF building structures (WMF, WBMF, and BMF) were used to form an average MICs for the period before 1930.

Based on these analyses, it can be concluded that even though the first interpretation is relevant to understanding the structure and possible usage of the MIC database, when used in modeling, adjustments are needed due to, for instance, incomplete inventory data. The impacts on estimated stocks and flows due to such limitations are discussed later in the text.

4.1.3. Sensitivity analysis: structural parameters in buildings

A sensitivity analysis was performed on structural variables at the building level. The buildings' footprint sizes and geometry, number of floors, basements in the building structures, and types of façades were the variables tested. It was determined that changes in all these variables influence the determined MICs. The number of floors and the presence or absence of basements have the greatest influence on the results. Therefore, SF residential buildings, which are considerably smaller structures than MF buildings, are the most sensitive to variations in these parameters.

4.1.4. International cross-comparison of MIC databases

The cross-comparison analysis of the MIC databases was performed by comparing the database constructed for Sweden to several case studies from diverse parts of the world: Vienna, Austria (Kleemann et al. 2016a), Northern and Central Europe (Wiedenhofer et al. 2015), the United Kingdom and Japan (Tanikawa and Hashimoto 2009), Germany (Ortlepp et al. 2016a), and China (Han and Xiang 2013).The MICs of all the case studies considered were compared according to the geographical context, material composition, temporal dimension, and structure types of the buildings. To be able to compare the results the MICs of the current study were adjusted to fit the units, material categories and classification types of the other studies (see Section 3.2, Article I). The most relevant findings derived from the analysis are the following:

- The results for Sweden reveal a higher wood-based and steel and iron material intensity than the other examined databases. High wood intensity can be explained by the large forestry resources available within the country. The higher steel and iron intensity can be explained by the assumptions made when defining the material categories. For instance, steel bars from reinforced concrete slabs were separated from the mineral-binding material category. However, it is not clear if this separation was done previously for other MIC databases because information about the material categories is not generally disclosed.

- An increasing trend in wood-based materials used in MF buildings in Sweden in the last two decades was confirmed by other studies, such as the one in Vienna, Austria, and Germany (Kleemann et al. 2016a; Ortlepp et al. 2016a). These results could signal a shift toward a higher use of wood-based materials in the construction industry.
- Contradictory values in the MIC databases created for similar geographical regions have been highlighted. For instance, the results of the current study are up to three times lower than the results of the study done for Northern Europe (Wiedenhofer et al. 2015). The discrepancy is explained by the structural specificity of the residential buildings sampled within the selected spatial boundaries. The current study, which relates to Sweden, has only wooden structure SF buildings included in the database, whereas the other study, which

relates to the Northern Europe, has a mix of wooden, concrete, and brick structures included in the database (Wiedenhofer et al. 2015). Further discrepancies in MIC databases were showed among other studies. Consequently, these findings suggest that the MIC databases differ more geographically than initially thought – within and beyond national boundaries or climate regions.

- Based on the cross-comparison analysis, a set of suggestions was provided on how to further report the developed MIC databases. The dimensions – footprint area, floor area (utilized or gross), height of floors, and height of the building – for each sample building included in the database should be displayed. These variables are particularly important because they allow adjustments to any unit type. Both the year of construction (or time period) and structure type should be presented for each building sample to allow comparison either by construction year or structure type. The categories of the construction materials should be demonstrated in the least aggregated form possible, and the category formation should be disclosed. The location of the sample building is important to ensure its representativeness of the database to a specific geographical boundary. The location is particularly relevant when the MIC database relates to large geographical regions, such as multiple countries.

- The cross-comparison analysis was also employed to validate the results. For example, although the MIC database for SF buildings in Sweden displayed lower values compared to most of the studies included in the analysis, the results were validated when compared only by structure type in the case study of the United Kingdom and Japan (Tanikawa and Hashimoto 2009). The difference observed is mainly explained by the fact that all the SF buildings in Sweden are wooden structures only, whereas all the other case studies featured a mix of wooden, brick, and concrete structures. Moreover, the MICs aggregated by structure type are the most accurate validation of the results in comparison to the periods or range intervals (Ortlepp et al. 2016a; Han and Xiang 2013; Wiedenhofer et al. 2015).

4.1.5. New approaches: data sources and replicability, documentation process, and analytical deliberations

One of the limitations for constructing MIC databases is the availability of data containing the historical documentation of the construction materials of buildings. In this thesis, specialized architectural books were used for the first time as the main materials for the formation of a MIC database. These books were an assembly of geographically and historically contingent architectural plans of buildings. From a replication point of view, it is important to know that similar material is available in other countries. Considering that studies at such a scale (with thousands of plans and advertisements from more than 30 municipalities) require enduring and costly work, the widespread availability of such materials is not likely. As an alternative, materials may be gathered from multiple sources, such as a mix of architectural and construction industry books, that have documented diverse periods of the whole historical development of construction materials in buildings. Therefore, although perhaps not easily available, specialized books are an important addition to the already commonly used data sources, such as study visits with specialists, architectural office databases, planning office archives, secondary sources (e.g., life-cycle inventories), and others.

Another aspect explored in relation to MIC database formation was the documentation process. A substantial effort was applied to this process by providing a detailed mathematical representation of the steps, descriptions of the database structure, the dimensions of the sampled buildings, and the categorization of the construction materials, among other. The aim was to enrich the methodological understanding and transparency for researchers and practitioners who wish to adopt a similar approach, and to complement the other documentations of MIC database formation.

Although several studies have worked on the construction of a MIC database, on most occasions, the results were further used for estimating the material stock (Kleemann et al. 2016a; Ortlepp et al. 2016b). On the contrary, in this study, the entire focus was devoted to the MIC database formation, results interpretation, sensitivity analysis, and international contextualization for the first time. It is recommended that further studies investigate MIC database formation. In fact, following the publication of Article I, two articles about MIC database have followed: one in relation to the transferability of MIC databases internationally (Schiller et al. 2018) and another regarding the compilation of a global MIC database for buildings (Heeren and Fishman 2019) – to which this database contributed.

4.2. Material stocks and flows

4.2.1. Main results

Residential stocks and flows were estimated in million metric tons at different administrative boundary levels. For example, the national material stock in residential buildings was estimated to 438 million tons. During the last 25 years (1991–2017), the material stock grew about 9% or 37 million tons. For the same period, the material inflows reached 54 million tons, and the outflows reached 17 million tons. Furthermore, beyond strictly accounting, the characteristics of the national stock were investigated. Among the six categories considered, mineral-binding materials, such as concrete, comprise the largest share of the in-use stock. Mineral-binding is followed by steel, aggregates, wood, and bricks. The stock is equally distributed between SF and MF residential buildings and dates mainly to the period 1951–1980. Considerable differences in the material composition, residential type, and age of the stock have been observed in urban context and among settlement types. These differences are deliberated later in the text.

4.2.2. Sensitivity analysis of the MIC database structure, limited inventory data, and uncertainty in the estimated stock

The sensitivity analysis was performed on the age-based MIC database structure as employed in the modeling of material stock (Article III). More specifically, the deviation from the average of the six material categories (e.g., wood-based, brick and ceramics, etc.) was assessed, which was defined for the four age classes (before 1930, 1931–

1950, 1951–1980, and after 1981). The results indicate a ± 30% variation in the estimated material stock. However, these results should be considered with care because they represent a maximum variation and thus a hypothetical condition. For instance, the results could imply that for the period before 1930, only WMF buildings were in the in-use stock, which is not the case. The variation can be explained by the fact that multiple building structures were incorporated within a single age class due to limited inventory data, and many construction materials have indicated less consistent values in the MIC database. Moreover, as revealed in the sensitivity analysis of the MICs, the structural differences at the building level (e.g., basement, number of floors, etc.) are a considerable variation factor. A way to decrease the uncertainty in the modeled stock would be to enrich the inventory data by conducting a statistical analysis on the buildings' structures. Similarly, further examinations of the construction materials, structural variations, and material categories formation with the help of on-site investigations, expert knowledge, and architectural materials are necessary to complement the already built MIC database (Kleemann et al. 2016b; Schiller et al. 2018; Gontia et al. 2018).

4.2.3. Cross-comparison analysis of stocks and flows

The cross-comparison analyses for the in-use stocks are commonly performed on a per capita basis. In the following lines, the estimated results for Gothenburg, Sweden are contrasted to the results from other studies. The residential stock per capita for Gothenburg was estimated at 62 tons. Similar values (13% higher) were exhibited for the city of Chiclayo in Peru, which, as of 2016, had a residential stock estimated at 55 tons per capita (Mesta et al. 2018). The two largest Chinese cities revealed two to three times lower residential stock per capita: 16 tons for Beijing and 25 tons for Tianjin (Huang et al. 2016). The level of economic development and the density of the built environment can explain the lower stock in these case studies. However, this argument is not valid for Manchester, which exhibits a residential stock of 38 tons per capita (Tanikawa and Hashimoto 2009). In contrast, other studies have demonstrated larger residential stock per capita. For instance, for Vienna, Austria, the residential stock was estimated at 131 tons (Kleemann et al. 2016a), and for the city center of Wakayama, Japan, the residential stock was estimated at 108 tons per capita (Tanikawa and Hashimoto 2009).A possible explanation for the case of Japan could be the national regulations due to seismic activities, which, consequently, have led to a higher material intensity (Tanikawa and Hashimoto 2009). In the case of Vienna, the considerably higher stock can be partly explained by the 15% higher MICs when compared to those used in the present study (Gontia et al. 2018). Cross-comparison analyses were also used to validate the estimated results. The in-use stock estimated for Gothenburg was partly confirmed by the study performed on the 25 countries part of European Union (EU 25) for which the stock was estimated at 72 tons/capita (Wiedenhofer et al. 2015). The relatively higher stock in the EU 25 can be explained by the high number of SF residential building areas, which could have a higher stock per capita than MF residential areas. Moreover, the difference can also be explained by the brick and concrete structures of SF buildings, which are predominant in the EU 25 (Wiedenhofer et al. 2015), in contrast to the mainly wooden structure SFs in Sweden (Gontia et al. 2018).

The estimated national flows of the residential buildings have been compared with results from top-down material flow accounting (Rosado et al. 2016) and an independently commissioned report (Deloitte 2015) (Article III). The estimated flows were validated within an order of magnitude. The differences are justified by the different methodological approaches employed. For example, it was demonstrated that top-down methods reveal higher results than bottom-up methods (Tanikawa et al. 2015; Cheng et al. 2019). Another point of divergence is the different objects compared. For instance, in the present case, the construction materials in residential buildings have been compared to all construction materials used for the maintenance and expansion of the built environment estimated in both cases for the same spatial contexts. To be able to compare the two results, rough calculations based on multiple assumptions have been done; and such calculations very likely contain errors. Nonetheless, these approaches are sufficient to partly validate the modeled stocks and flows of large spatial contexts.

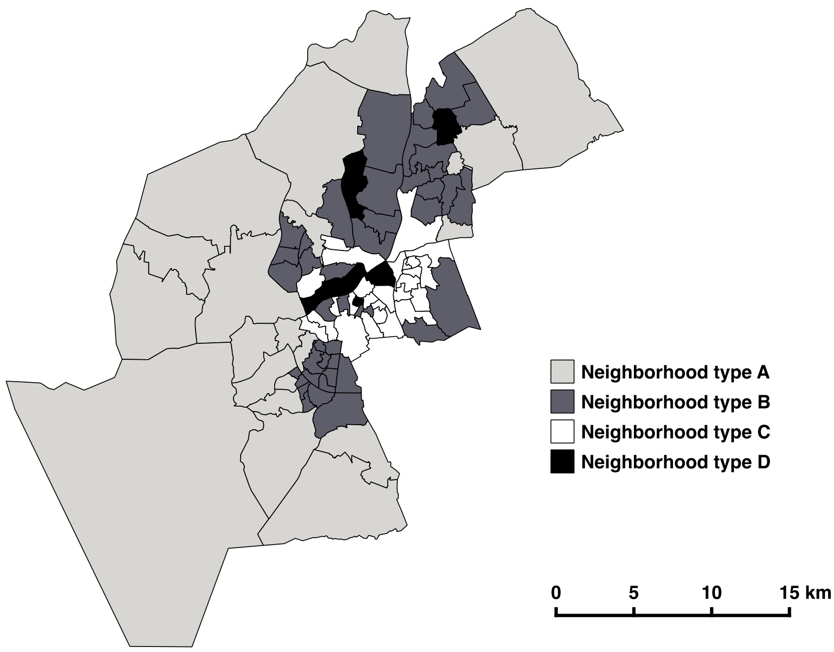
4.3. Spatial analysis

4.3.1. Urban material stock: results and sensitivity analysis

The main aim of this analysis was to identify urban areas that have similar material stock characteristics. For this purpose, material stock indicators were defined at the neighborhood level and clustered with k-mean algorithms. The analysis was employed for the municipality of Gothenburg. The results are displayed spatially in Figure 7a, and the mean values of each indicator for the formed clusters are displayed in Figure 7b.

Four neighborhood types were identified through multiple runs of the algorithm. Each of the clusters has a particular material composition, age class, and spatial characteristics. It is evident that SF residential buildings clustered into a single neighborhood type, and MF buildings formed three typologies. Neighborhood type A is characterized by SF buildings and is located at the outskirts of the city (Figure 7). Wood-based material accounts for 12% of the stock, which is the highest among the four neighborhood types. Neighborhoods of type B are characterized by MF buildings, which are located between the outskirts and the central area (Figure 7). The stock is mainly composed of mineral-binding materials, which comprise about 70% of the total. The largest share of the stock dates from the period 1950–1980. Neighborhood type C consists of MF buildings and is centrally located. Furthermore, 74% of the stock dates to before 1950 (Figure 7). These neighborhoods have a high brick and ceramics content (24%), which is the largest of the four neighborhood types. Neighborhood type D is populated with MF buildings constructed primarily after 1981. These buildings are positioned centrally and are intermediary in the city's geography. Most of the stock is made from mineral-binding materials (58%), but the percentage of steel, at 17% of the residential stock, is noticeably high (Figure 7). Cumulatively, the stock for the four neighborhood types distributes as follows: 7.6 million tons for type A, 13.7 million tons for type B, 11.2 million tons for type C, and 1.6 million tons for type D.

a)



b)

	Material stock						Residential type		Age class		
	W	B	M	S	I	O	SF	MF	Before 1950	1951-1980	After 1981
Type A	12%	5%	56%	8%	11%	8%	90%	10%	25%	43%	32%
Type B	4%	7%	70%	2%	12%	5%	10%	90%	5%	89%	6%
Type C	9%	24%	44%	7%	9%	7%	11%	89%	74%	16%	10%
Type D	5%	11%	58%	3%	17%	6%	11%	89%	14%	15%	71%

Figure 7. Clustering results for the three indicators in Gothenburg: (a) the spatial representation and (b) the tabulated values as percentages for each indicator and neighborhood type; W: wood-based material, B: brick and ceramics, M: mineral-binding materials, S: stone and aggregates, I: iron and steel, and O: other/miscellaneous construction materials.

Besides the k-mean algorithm for which the main results were displayed above, two other clustering algorithms (hierarchical (Murtagh 1985) and k-median (Cardot et al. 2012)) were tested for the same data sample. The analysis revealed a) the outliers in the datasets that do not fit any of the formed clusters and b) the possible weak cluster formations, such as Neighborhood type D.

4.3.2. National analysis among settlement types: retrospective stocks and flows, in-use stock characteristics, and spatial distribution

The main aim of this analysis was to uncover the characteristics of national material stocks and flows in residential buildings when considering different settlement types. Sweden’s 290 municipalities classified into eight settlement types were utilized as a case study.

The in-use and retrospective stocks, inflows, and outflows are listed in Figure 8. The results indicate that in the last 25 years, the material stock in Sweden has increased the most in LCs and CLCs (Figure 8). In fact, 63% of the national stock increase is concentrated in these two settlement types. On the contrary, RMs and CSTs reveal a decrease in material stock. For the same period, particularities in material flows were also depicted. For instance, MTs exhibited the highest inflow and outflow, CLCs showed no outflows, and RMIs revealed a 10% stock renewal (Figure 8).

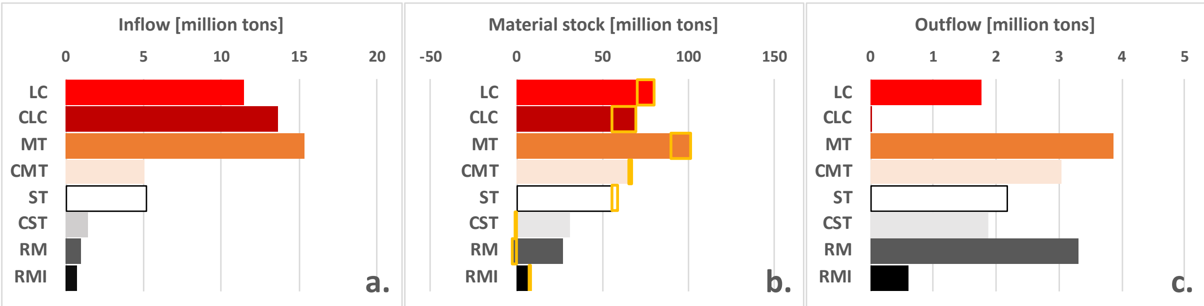


Figure 8. Material stock and flows by settlement types: (a) material inflow (1991–2017); (b) in-use material stock (2017) and areas marked with yellow lines representing the material stock accumulated in the period 1991–2017; (c) material outflows (1991–2017); LC: large city; CLC: commuter municipality to LC; MT: medium-sized town; CMT: commuter municipality to MT; ST: small town; CST: commuter municipality to ST; RM: rural municipality; and RMI: rural municipality with a visiting industry.

Figure 9 indicates the different characteristics of the in-use stock among the settlement types. The results show that the material composition of the stock differs by settlement type. Whereas brick and steel demonstrate a higher stock in larger settlements, wood and aggregate reveal a larger stock in smaller, commuter, and rural settlements. These variations are explained by the different proportions of residential building types and the age of the stock in settlements (Figure 9b,c).

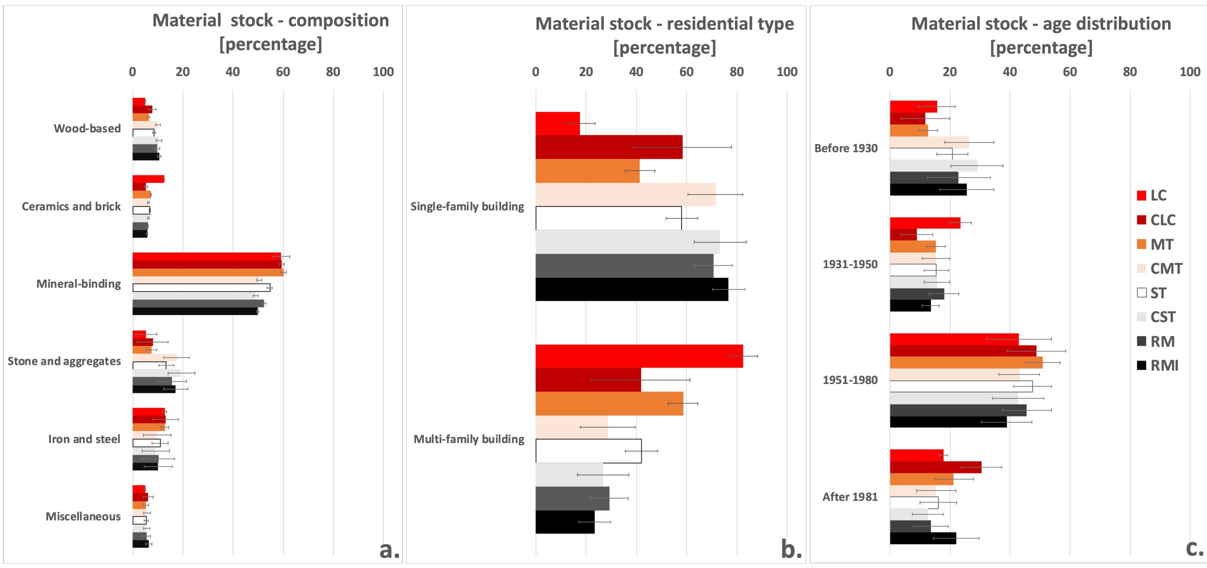


Figure 9. Average percentages and standard deviation of the (a) material composition, (b) residential type, and (c) age distribution of the stock in the eight settlement types. The average percentage is derived from the mass of the material stock.

Figure 10 illustrates the spatial distribution of the in-use stock and stock density per land area in each municipality in relation to the settlement types. The results indicate that the majority of the municipalities, regardless of the settlement type, have an in-use stock below 2 million tons and a low density stock below 3 ktons/km^2 (Figure 10). Furthermore, it can be observed that the largest and densest stock accumulates in LCs in the southern part of the country and near the coastline. Inland, the largest and densest stock accumulates in MTs, along with the transportation networks, which connect the LCs in Sweden and the capitals of the neighboring countries: Oslo, Norway and Copenhagen, Denmark (Figures 5 and 10). These results suggest that 1) transportation infrastructures and urbanization positively feedback to each other, and 2) there is lock-in phenomenon of dense stock accumulation in LCs and the corridors that form between them. These findings are relevant for guiding national policies in relation to the circularity of construction materials in built environment. Moreover, these intensively built corridors can be used to restrict development and preserve more of the natural environment.

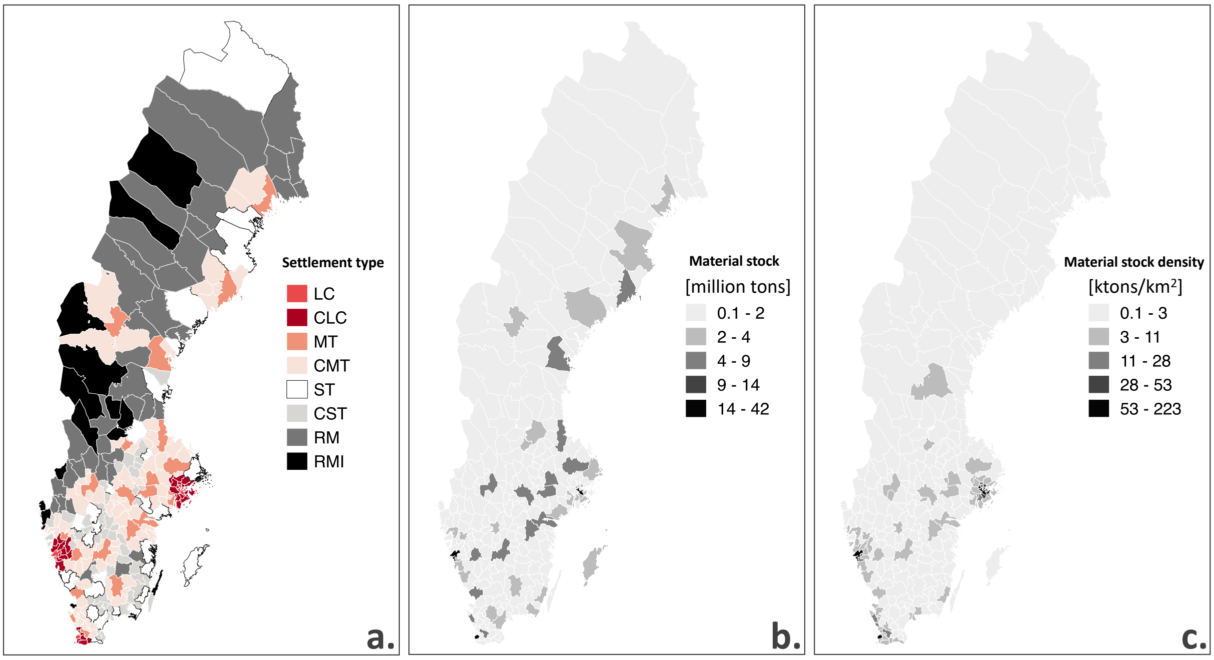


Figure 10: The spatial distribution of (a) settlements, (b) material stock, and (c) material stock density in the 290 municipalities of Sweden; ktons = 10^3 tons.

It is commonly known that CLCs are built on low density. These settlement formations are known as urban sprawl and have received much criticism, not least from a resource efficiency perspective. However, in the context of Sweden, CLCs show on average a considerably higher stock density (25 ktons/km^2) than MTs (5 ktons/km^2). Moreover, MTs have the largest accumulated stock of all the settlements types (Figure 8b) and are surrounded by even lower density urban sprawl - the CMTs. The results suggest that urban sprawl in relation to material stock density should be also interpreted nationally or at larger regional contexts. If a single large metropolitan area is independently assessed, the results that overlook the national context could lead to inadequate conclusions in regard to material stock density, and, consequently, inappropriate policy guidance. However, to confirm these findings it is necessary that the stock density assessment is complemented with in-depth analysis on (a) land use in the two different settlement types (CLCs and MTs) and (b) the average national results within a settlement type comparative to specific municipalities – for example some of the CLCs near Stockholm municipality show much higher density (above 200 ktons/km2) in comparison to the national average.

5. Conclusions

The rapid human development of the last century and its implication for the future is presently under scrutiny. Questions have been raised on the sustainability of the predominant socio-economic system, which demonstrates multiple limitations, including a malign, linear material metabolism. This linear trend cannot continue indefinitely; therefore, a higher material circularity is demanded. To attain circularity, knowledge about material stocks, derived flows, and their temporal and spatial dynamics is required.

The main goal of this thesis was to uncover the material metabolism of residential buildings in Sweden. Three major methodological steps were considered. First, a historical database of the material intensity for residential buildings in Sweden was constructed. Second, the resulting database and inventory datasets were used to model bottom-up material stocks and flows. Third, new approaches were employed to analyze the spatial distribution of the material stocks and flows in urban and national contexts. Finally, when relevant, cross-comparison and sensitivity analyses were performed to further enrich the results.

The major findings of this thesis are the following:

- The constructed database revealed distinctive trends in terms of material intensity and composition for residential buildings in Sweden. The sensitivity analysis indicates that SF buildings are the most vulnerable to changes in the structural parameters of buildings (e.g., the number of floors, basements, etc.). A cross-comparison analysis revealed how material intensity and composition in residential buildings differs geographically in the international context. The constructed database contribute to the establishment of a global MIC database. New data sources were explored, and methodological advancement was accomplished through the process of database formation.

- Residential stocks and flows were estimated in million metric tons at different administrative boundary levels. Among the six categories considered, mineral-binding materials, such as concrete, comprise the largest share of the in-use stock, regardless of the spatial boundary assessed. Similarly, regardless of administrative boundaries, the stock dates mainly from the period 1951–1980. In an international context, per capita stock was found to be a medium estimate, and was partly validated by previous studies conducted in a similar geographical context. What's more, further analysis showed that an incomplete inventory spatial data influences the MIC database structure employed in the modeling, and consequently increases error in the estimated material stock.

- The spatial analysis approaches employed in this thesis enhanced the understanding of the construction material stocks and flows in residential buildings. The material composition of the in-use stock in residential buildings reveals distinct patterns in the urban geography and nationally among the eight settlement types. These particularities in material composition are due to variations in building stock characteristics: residential building type and period of construction. Furthermore, specific spatial characteristics of retrospective material stocks and flows were identified among the settlement types. In the last 25 years, two-thirds of the national stock growth took place in LCs and CLCs. Not surprisingly, RMs and CSTs showed a decrease in stock. TMs showed the highest inflow and outflow, CLCs showed no outflows, and RMIs showed a high stock renewal. Finally, a lock-in spatial expansion of the stock was identified in the national geography, namely a high stock density in the metropolitan areas and the corridors that formed between them. This last finding is relevant for designing national policies in relation to material circularity in built environment and expansion of human development into the natural environment.

6. Limitations and outlook

In this chapter, ways in which this work could be continued are suggested. Some of the proposals are directly related to gaps in the current work, whereas others are broader suggestions to advance the field of knowledge.

The constructed MIC database for buildings in Sweden is not complete and therefore requires further improvements. First, the database did not cover the brick load bearing structures of SF buildings, which are common in the southern part of Sweden (Björk et al. 2009). Second, for MF buildings, the period after 1990 should be complemented by adding more buildings, considering that only four buildings from this period were included in the database. Third, the database contains little information about some of the finishing materials such as the coverings of floors, roofs, façades, doors, and windows. These particularities are relevant when assessing flows related to large-scale refurbishment (York Ostermeyer 2017). Similarly, materials in wire and pipe networks in the buildings were not included in the constructed database. Although these networks comprise a relatively small share of the total mass of a building from a material perspective, such as copper contents, these networks are important (Kleemann et al. 2016b). Furthermore, about half of the building stock is non-residential, and although some work has been completed for Sweden in Article II, an expanded national MIC database should be developed. Finally, the database should be updated periodically by interested parties with the most typical building structures of the time. This task is necessary considering that the materials used by the construction industry are, as indicated historically, constantly changing.

The MIC database presents important results at the building element level, but little was done with this information in this thesis. An analysis of the materials at the building structural level could support architectural projects, which consider directly re-using building elements in new structures (Hradil et al. 2014). A first attempt to understand the potential of circularity at the building element level has been accomplished by Arora et al. (2019) in a study of Singapore. Future studies should focus on assessing the quality of decommissioned elements, to systematically quantify the stocks and flows at the building element level, and exploring technical and architectural modalities in which the elements could be reintegrated in new structures.

The spatial analysis approaches explored in this thesis should be further developed and explored. Regarding the spatial analysis of urban stock, further work should be done to develop indicators, test other spatial divisions of urban stock, and contrast different clustering algorithms. In terms of case studies, it would be interesting to apply the proposed approach to megacities or to compare multiple cities. Regarding the settlements approach, future work should be applied on multiple components of the built environment (other types of buildings, roads, pipes, etc.), not only on residential buildings, to determine the total in-use stock in the built environment. In terms of case studies, it would be interesting to assess the residential or total material stocks and flows of nations other than Sweden or to analyze larger geographical areas beyond nation state boundaries. The two spatial analysis approaches developed in this thesis should be viewed as complementary efforts to the already developed field (Han et al. 2018; Kleemann et al. 2016a; Tanikawa et al. 2015). At the same time, all these multitude approaches demonstrate that different spatial analyses lead to different findings and that there are many ways in which the spatial analysis of stocks and flows could be further explored; therefore, any further attempt in this regard is highly recommended.

In this thesis, much attention was given to the spatial analysis of material stocks and flows in Sweden. However, a long-term retrospective assessment of the material stocks and flows should be considered in future research. One way to achieve this aim would be to utilize historical maps and aerial images, which document the changes in the built environment (Tanikawa and Hashimoto 2009). Furthermore, the temporal analysis done in this thesis was only retrospective. Modeling prospective stock accumulation and future flows of construction materials should be considered as a continuation of this work. This task could be achieved with the already developed MIC database and socio-economic indicators as exemplified by the demand-driven approach (Müller 2006). It would be interesting to model the use of different emergent construction materials related to the embodied energy and environmental impacts, such as global warming potential.

The age distribution of the in-use material stock in residential buildings was determined in this thesis. However, to determine the outflows derived from the in-use stock, a deeper understanding of the lifespan of buildings in Sweden and the factors that influence their demolition is relevant and thus recommended. The end of life of buildings is a complex matter because in most cases, the design lifetime of the building does not indicate the demolition date (Miatto et al. 2017). For instance, in the case of China, it was demonstrated that internal factors (e.g., construction quality, building type, etc.) have less influence on the end of life of buildings when compared to external factors, such as the local economic context (Liu et al. 2014).

The knowledge developed in this thesis could help organizations and governments to design short- and long-term policies and strategies to increase material circularity. However, at the organizational level, circular strategies are at an early stage of development, and much remains to be done in this direction (Pauliuk 2018). Advancement is especially needed regarding incorporating the systemic analysis of stocks and flows into the routines of organizations. As a solution to bridge the knowledge gap between research and practice, it is proposed here that the related actors are directly a part of the knowledge production – a process known as knowledge co-production or transdisciplinary research (Robinson 2008; Watson 2014). Furthermore, from a governance perspective, it is necessary to determine the gap between policy and human behavior or social and natural phenomena to increase the certainty that progress is made toward defined goals.

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